Geist

Electrical Performance Of The Magneto-Generator

ELECTRICAL PERFORMANCE

OF THE

MAGNETO-GENERATOR

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED BY

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Recommendation concurred in :

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Edward C. Schmidt

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ELECTRICAL PERFORMANCE OF THE MAGNETO-GENERATOR.

Introduction.

There are in general two forms of electrical ignition systems; the low tension, commonly called the "make and break", and the high tension, or "jump spark". In the low tension system the spark is produced by breaking an electro-magnetic circuit that has been energized during a period of make. The spark of course appears at the points of break, so that the interruption of the circuit must occur within the cylinder of the engine. In the high tension system, the energy stored during make of the primary circuit is suddenly transformed at break, by means of the secondary circuit, to a voltage that is sufficient to over-come the dielectric strength of a gap con- sisting of two permanently fixed spark points.

Both of these forms of ignition represent good practise in their respective fields. The field of the low tension system is in general internal combustion engines in which the operating speed is low enough to permit the use of the necessary make and break mechanism. Because of the fact that this mechanism must produce a relatively long and quick break, besides enduring the heat and pressure of the cylinder, its proportions must be such that it is unfeasible to operate it on engines firing more than 600 to 700 times per minute, as the upper limit and is rarely used on engines of even that speed.

The simplicity and low cost of the low tension system make it ideal for the single cylinder, four cycle, slow

speed engine, of which class the farm engine is the most prominent. Engines of this class usually operate at a speed of about 400 to 600 r.p.m. so that the ignitor therefore is operated at half this frequency of impulses.

For the high speed engines and especially the multicylinder units, the high tension ignition system has an undisputed field, because of the simplicity of the spark plug and of the ease with which the high potential energy can be distributed to the different cylinders from a single generative source. The primary breaker, which may be the vibrator of an induction coil or the mechanical breaker of a magneto, depending upon the type of system used, can readily be designed to endure the frequency of impulses required by the high speed engines.

There are of course engines where either form of ignition could be used with equal results, so that the choice depends upon detail considerations that arise with the requirements of the particular installation. Cost is usually a very important consideration. In the United States, the tendency is to use the low tension system whenever practical, because of its simplicity, its durability and low cost, but in Canada and in most foreign countries, the high tension system has the more general use for all classes of engines.

The first electrical ignition systems used batteries, as the generative source of energy, in connection with coils for the storing and transforming functions. These same systems represent the common battery ignition practise of the present time. For the low tension system, a simple choke coil of suitable characteristics serves to store the energy during make that during break is delivered to the spark, while for the high

tension system, a vibrating induction coil serves to store and transform the energy for the jump spark. There is a tendency at present to use a simple transformer with a mechanical breaker, doing away with the vibrator and the timer, for the breaker serves as the timer, making a battery system that gives one hot spark, at the action of the breaker, instead of the multiplicity of weak sparks given off at high frequency by the vibrating induction coil. This practise is an endeavor to duplicate the efficient ignition spark received from the self-contained high tension magneto.

The cost of battery renewals created a field for the mechanical means of energy supply and consequently the dynamo was called upon to take the place of the battery. The first ignition generators were designed to take the place of the battery only and to perform no other function in the ignition system, so were designed as commutating or direct current machines of bi-polar constuction. Some of these machines were designed to excite their own field, while others used permanent magnets as the source of magnetic flux. These machines were friction driven from the flywheel of the engine in most cases, with centrifugal governors for speed regulation.

Like the battery ignition system, these dynamo systems maintained the advantage in that no fixed timing relation between the armature and the engine piston was required, but had a disadvantage in starting the engine, due to the speed of operation required, that is of course absent in the case of battery ignition. It is for this reason that the battery ignition system was not entirely eliminated and no doubt never will

be supplanted by rotary magnetos. Of these two classes of generators, the machines using permanent magnets had an advantage both in the required operating speed and in the general size and cost for any given rating. The low armature resistance of these machines accounts for the efficient sparking action found in this type of system, as compared to batteries in which the internal resistance is always increasing with the age of the cell, but the mechanical short comings coincident to their commutators, friction drive and to centrifugal governors, more than offset this electrical advantage. It is, no doubt, these mechanical considerations that have caused the short life of this type of ignition system.

Following the direct current generators came the alternating current type of magneto generator. In this type of machine, still bi-polar in construction, all the available coil space is utilized for one coil, doing away with the commutator and substituting the collector ring and ground brush instead. The increased number of turns put into the one coil increases the coefficient of self-induction of the circuit to such a value that a choke coil is not required. The magneto therefore generates and stores energy for the spark in its own windings. A further effect of the coil characteristics of this type of machine is that the operating speed is very materially reduced. While the direct current machines mentioned above were required to operate at from 1800 to as high as 3000 r.p.m., in most cases, alternating current types can readily be designed to give satisfaction at speeds of 400 to 600 r.p.m. The low tension magneto in connection with a make and break ignitor plug therefore represents a complete ignition system. For a high

tension system of the same general class, the same type of
machine is wound with both primary and secondary coils, and is
equipped with a mechanical breaker and a suitable condenser.
For multi-cylinder engines, a distributer forms an integral
part of the magneto structure.

Because of the fact that the machine is alternating
in its performance and gives two electrical impulses per revol-
ution of the armature, it is evident that there are positions
of the armature with reference to the pole pieces at which
little or no energy is stored in the winding and consequently
no ignition spark can be received for these positions, so that
a fixed relation must exist between the armature and the piston
of the engine served. The magneto is therefore gear driven
from the crank shaft of the engine. Furthermore, since for
starting the engine, the ignition spark is desired later on the
piston stroke than for the running condition, so as to prevent
pounding or back firing, and since the armature is exactly
fixed with reference to the piston, it is evident that a spark-
ing range must be an inherent characteristic of the electrical
action of the magneto itself. In most engines a variation in
firing of 30 degrees of flywheel is required, so that if the
magneto is driven at engine speed, its sparking range must be
at least 30 degrees. If the magneto is driven at twice engine
speed, it must therefore have twice this range. Most magnetos
of this type have a sparking range of from 30 to 45 degrees
depending upon the design.

Inspite of the low operating speed required for
energy generation, starting is also uncertain in this type of
system, especially in the larger engine sizes, because of the

fact that the magneto is gear driven from the engine and has a starting speed that is proportional to the speed at which the engine is turned over during starting. This disadvantage has been overcome by the use of springs as a means of magneto operation, making what is known as an oscillating type of magneto generator. In this system, the energy of the ignition spark that will be received depends upon the energy contained in the stretched springs, rather than upon the speed at which the engine operates the magneto, so that the oscillator system will give the same ignition spark regardless of the engine speed, and consequently starting is easily accomplished.

Due to the fact that the timing of the oscillating magneto is taken care of entirely by mechanical means, the magneto itself needs have only enough sparking range to take care of the wear that occurs in the spark points. This wear in terms of armature motion amounts to but very little. For this reason a magneto designed for rotary service does not have the same electrical characteristics that are required in the oscillator or visa versa. It is therefore evident that the characteristics in a magneto, necessary to the best results, must be in accord with the requirements of the engine and the method of its operation.

The manner in which the rotary magneto generates, stores energy over its range, and delivers the energy to an ignition spark, makes its phenomena interesting. For the purpose of this paper, therefore, the writer has selected a low tension magneto of good design; one of the bi-polar, wound armature type, and will attempt by flux diagrams to show in a general manner the electrical performance of this type of mach-

ine. A more special accompanying treatment, using oscillograms
and other electrical measurements taken from this machine, will
be used to illustrate more clearly the phenomena of open circuit
operation, short circuit operation, and of sparking of the
system. Calculations based upon the data represented in these
measurements, leading toward a valuation of the ignition spark
in thermo-electrical units of heat and of the energy distribut-
ion during the phenomena of sparking for the different armature
positions, will be included as part of the scope of this paper.

A further purpose of this paper is to illustrate an
experimental means of analysis of ignition systems, that can be
carried out with the facilities usually found in laboratories
of manufacturing establishments. The accuracy embodied in the
results, from a quantitative standpoint, is compatable more
with engineering than with scientific study.

CHAPTER II.

CIRCUIT CHARACTERISTICS.

The most common form of magneto generator is the so called "wound armature" type, consisting of a coil wound upon an armature that is free to turn between the poles of a permanent "horseshoe" magnet. The pole pieces and the armature are so proportioned, that the best possible electro-magnetic relation exists in the machine for the generation, the storage and the utilization of electrical energy. These proportions have an effect upon the circuit characteristics, as well as upon the nature of the electrical forces produced. The clearance air-gap is usually made as small as is mechanically possible, because the efficiency of the machine depends very much upon it. A clearance of .003 inches is the common practise.

The manner in which the electrical current will obey the generated electrical forces in an electro-magnetic circuit depends upon the characteristics of the circuit, as well as upon the nature of the forces, so that it is well to consider at this time the characteristics of the magneto circuit. Like any other electro-magnetic circuit, the magneto has the two characteristics called resistance and self-induction. Resistance in the ordinary sense represents the opposition, to current flow in a circuit, that is a function of the cross section of the conductor, its length, nature of conducting material and temperature, i.e., it refers to the opposition to measurable current flow.

Due to the fact that in circuits where the energy changes periodically, an iron loss, that can be attributed to

the resistance of the iron to eddy currents and to the friction of the molecules opposing magnetic reversals, occurs, and due to the fact that it is often convenient to express all electric- al losses as a single resistance loss, it is common to express all of these resistances in what is known as an effective resist- ance. For this treatise, however, the ordinary meaning of resist- ance will be used and the effects of eddy currents and hysteres- is will be considered separately as the iron losses.

,In the magneto, the value of the resistance of the coil is of course a constant, so that for the closed circuit condition the resistance does not change. However, during the period of sparking, the spark resistance is suddenly inserted in series with the coil resistance making the circuit resist- ance for this period equal to "R $+$ r_s". The spark resistance "r_s" is of course variable in value. The resistance "R" of the coil of the particular magneto under consideration was meas- ured by means of a Wheatstone Bridge and is 4.02 ohms.

Self-induction is the other characteristic, and is best defined by Henry's law, which states, that a circuit has a coefficient of self-induction of one henry if a current, flow- ing in that circuit and changing at the rate of one ampere per second, induces a counter electro-motive-force of one volt. Mathematically this definition may be expressed by,

$$E_c = - L \frac{\delta i}{\delta t}$$

This induced e.m.f. will oppose the current forcing e.m.f. with increasing current changes but will aid it when the current decreasing changes take place. The coefficient of self- induction "L" is merely an expression for the degree of inter-

relation existing between the electrical and its interlinked magnetic circuit. Henry's law may be shown to be exactly anal- agous to the law for ordinary electro-magnetic e.m.f. generation with the exception that the flux component is the reactive flux instead of the excitation flux.

In the magneto, the coefficient of self-induction varies very materially for the different positions assumed by the armature during its rotation. From a study of the diagrams of the following chapter, it will be seen that the best possible path for the reactive flux set up by the coil exists when the armature is in the position shown in Fig. 3, so that for this position the coefficient of self-induction will be a maximum. This is quite evident for at this position the flux has the most complete soft iron path through the armature and both pole pieces. The lines of force actually shown in Fig. 3 re- present the excitation or main flux and must be distinguished from the reactive flux which forms interlinking loops with the coil during closed circuit. The magnet bars must not be consid- ered as a path for any but the excitation flux for the reactive can never attain a value that is even equal to the excitation flux which it opposes. Likewise it will be seen that the self- induction will be a minimum for the position represented in Fig. 2. The change in its value from the maximum to the min- imum, since it is directly a function of the permeability of magnetic path will be very abrupt for the positions in the neighborhood of Fig. 3, but very gradual as the armature ap- proaches Fig. 2, as is illustrated clearly in the curve Fig. 1.

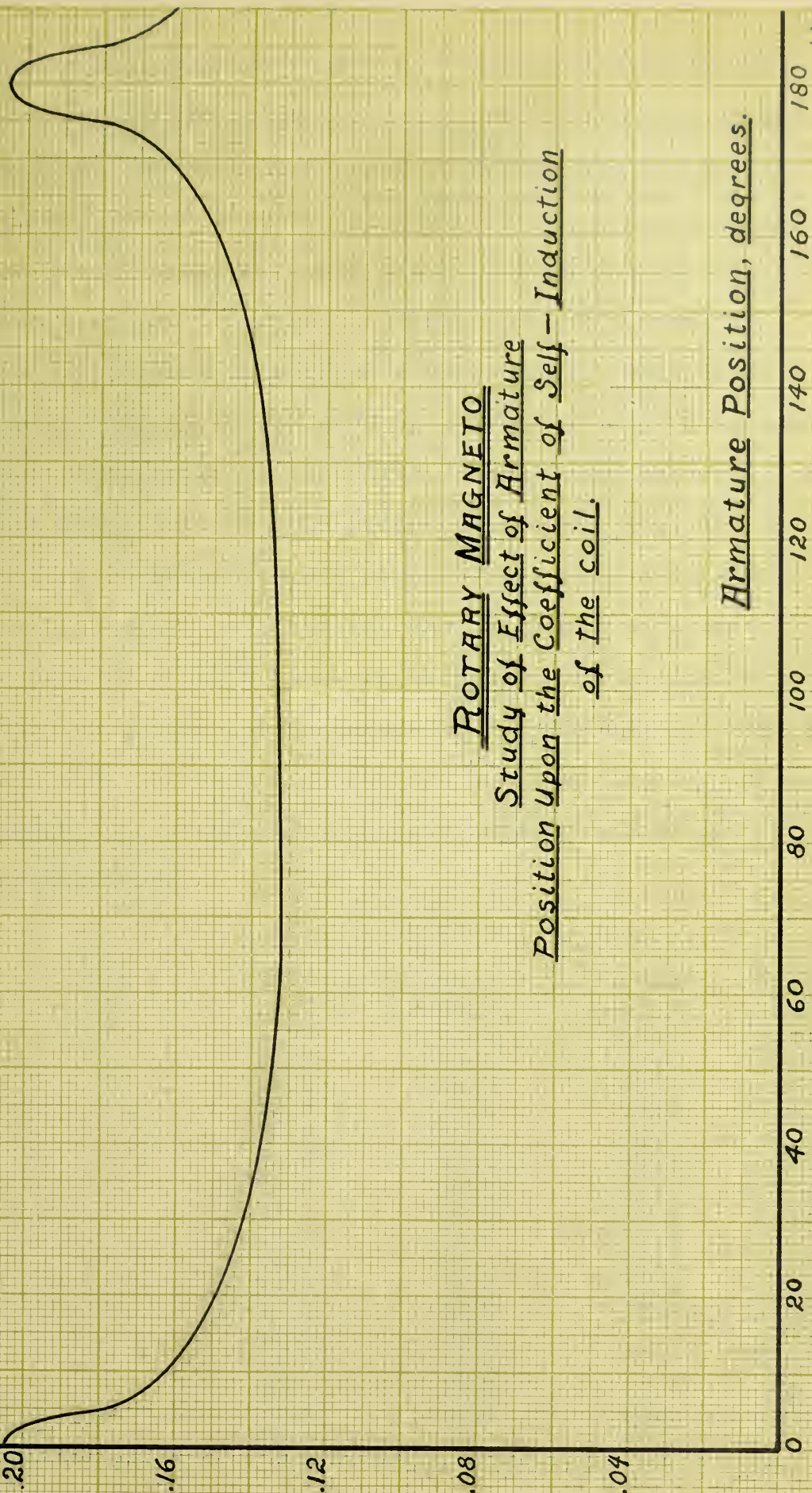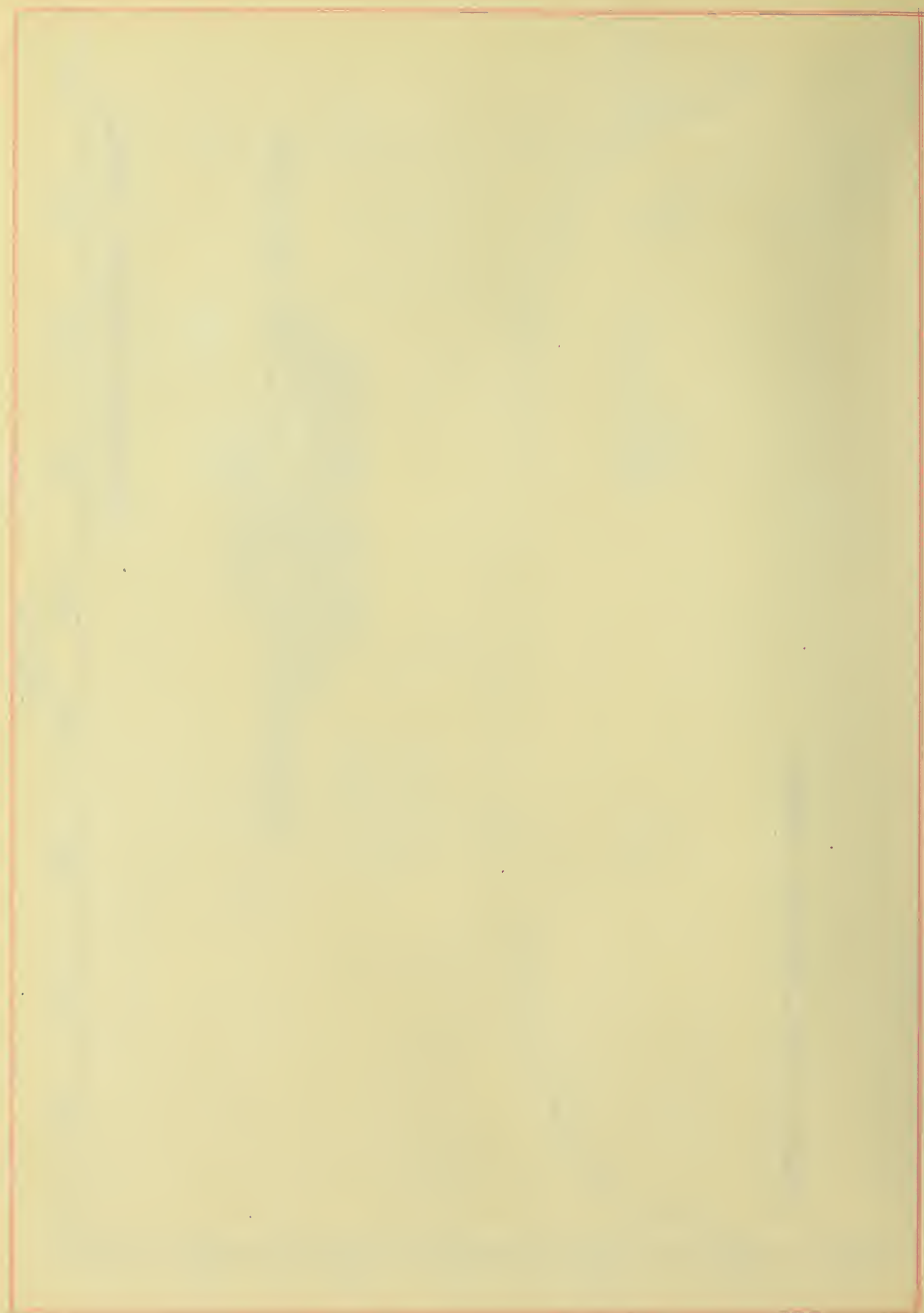In order to determine the relation between the value

ROTARY MAGNETO
Study of Effect of Armature
Position upon the Coefficient of Self—Induction
of the coil.

Fig. 1.

Armature Position, degrees.

Coeff. of Self—Induction, henrys.

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of inductance and armature position, it is only necessary to set the armature at different positions and measure the inductance by some standard method. It is best to remove the magnet bars for this test. Such a test of this machine was made by impressing an e.m.f. of known frequency and of sufficient value to force a small amount of current through the coil, upon the machine, and the value of current together with the voltage required measured. As low a value of current as can be accurately handled is desirable so as to keep the effects of iron losses that are coincident to this method as low as possible. It is also desirable that the wave shape of the impressed e.m.f. be as near sinusoidal as possible. The following tabulation gives the results of this test. In this test the angular position represented by zero is taken arbitrarily as that of Fig. 3. The measured and calculated quantities are symbolized by the letters adopted as standard by the American Institute of Electrical Engineers.

Angle	I	E	Z	X	L
0	.262	20.2	77.1	77.0	.204
5	"	17.4	66.4	66.3	.176
10	"	16.0	61.1	61.0	.162
15	"	15.2	58.0	57.9	.154
20	"	14.8	56.5	56.4	.149
35	"	14.0	53.4	53.3	.141
55	"	13.2	50.4	50.3	.133
75	"	13.0	49.6	49.5	.131
90	"	13.0	49.6	49.5	.131
115	"	13.1	50.0	49.9	.132
135	"	13.6	51.9	51.8	.137
155	"	14.5	55.4	55.3	.146
160	"	14.8	56.5	56.4	.149
165	"	15.2	58.0	57.9	.154
170	"	16.0	61.1	61.0	.162
175	"	18.8	71.8	71.7	.190
180	"	20.3	77.5	77.4	.205
185	"	17.7	67.6	67.5	.179
190	"	15.9	60.7	60.6	.160

In the above calculations "Z" in each case is obtained by dividing "E" by "I". The value of "X" is obtained by taking the square root of the difference of the squares of "Z" and the value of "R" previously determined. Since the wave shape was practically sinusoidal, the following equation can be used.

$$L = \frac{X}{2\pi f}$$

where "f", the frequency, in this test was 60 cycles. By the use of this equation the value of "L" for the different armature positions was calculated.

The above results are plotted to scale in the diagram Fig. 1, and shows clearly the approximate relation between the coefficient of self-induction and the armature position over one half revolution. The other half will be identical with it. Due to the fact that the iron losses cause some error in the above determination and because of the fact that they will be most pronounced for the positions in the neighborhood of Fig. 3, there is no doubt but what the true maximum value is slightly higher than is shown by the test.

Particular attention is called to the sudden drop in the value of inductance that occurs for the position of the armature immediately after that of Fig. 3. A comparison with the short circuit current wave that will be shown in one of the succeeding chapters, will make it clear that the sudden rise in current for this same position is partly due to the sudden drop in the inductance that occurs simultaneously with it.

In any electrical circuit, the function of inductance

is to delay the rise of current, under any voltage influence, toward the maximum that it would otherwise attain, limited by resistance only, and under conditions of changing voltage, to delay the corresponding subsequent current changes, that would otherwise follow directly and exactly in phase.

For this reason it is often desirable to express the effect of inductance of the circuit in terms of a time constant that will express the amount of the delay in standard units of time. The units in which the circuit characteristics are expressed are such that under a constant e.m.f., the time in seconds for the current to attain 63.2 percent of its maximum is obtained by dividing the value of the inductance, in henrys, by the value of the resistance in ohms, or

$$T, \text{ seconds} = \frac{L, \text{ henrys}}{R, \text{ ohms}}$$

It is impractical to use this time constant in magneto considerations except in a rough way because of the fact that the impedance voltage is impossible to measure directly, and its use in connection with the open circuit e.m.f. is in need of modifications due to the ever present armature reaction that accompanies current flow.

This time constant nevertheless has a decided influence upon the short circuit wave form and therefore upon the resulting range of the energy surge accompanying it, so that it is desirable to know what physical machine dimensions affect it.

The inductance of a circuit can always be increased very rapidly by increasing the number of turns of the coil, for inductance is directly proportional to the square of the turns

under assumptions of constant magnetic reluctance. Increasing
the turns however for a given coil space does not materially
affect the time constant, because the resistance of the con-
ductor increases also as the square of the decreased diameter
of the wire necessary, unless of course a better space factor
is obtained. The best method of increasing the inductance is
therefore through a decrease of the reluctance of the magnetic
path, most important of which is the clearance air-gap. It is
partly for this reason that the air gap is made as small as is
practical, besides the increase in excitation flux that also
results.

CHAPTER III.

OPEN CIRCUIT OPERATION.

Since the open circuit operation of the magneto is the simplest and because it can be used as a reference condition, it will be considered first. During open circuit no current can flow, i.e., no energy will be generated in the coil, so that the electro-motive-force generated at any instant at the terminals of the coil will give a fair idea of the manner in which the armature rotation produces magnetic changes with reference to the coil.

To facilitate a discussion of the open circuit operation, flux diagrams showing the armature in distinctive positions will be resorted to first. The following two illustrations represent in a diagrammatical way, a magneto, showing the magnets, the pole pieces and the armature with its coil. In Fig. 2, the armature is shown in the position in which practically all of the flux passes through the coil, while Fig. 3 shows the armature in the position in which none of the flux passes through the coil, but is by-passed by the armature face tips.

As the coil is rotated with the armature, it is evident that the flux will be shifted out of its interlinked position with the coil and then back into it again for each half turn of the armature, so that the flow of flux is reversed with respect to the coil twice for each revolution. The result is that two impulses of electro-motive-force are generated, each of opposite polarity and of a value that is at any instant pro-
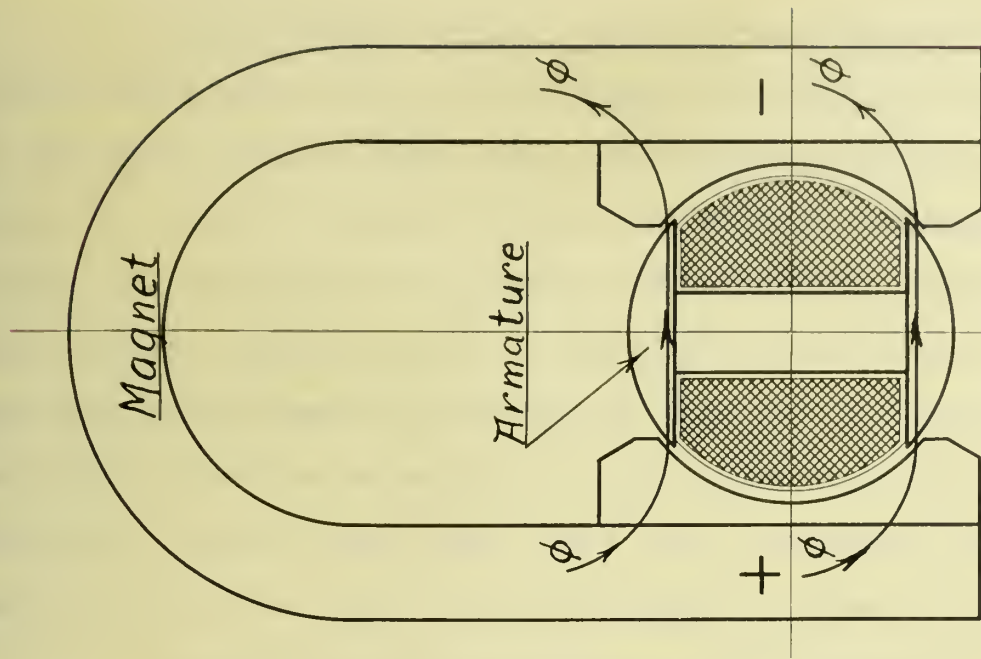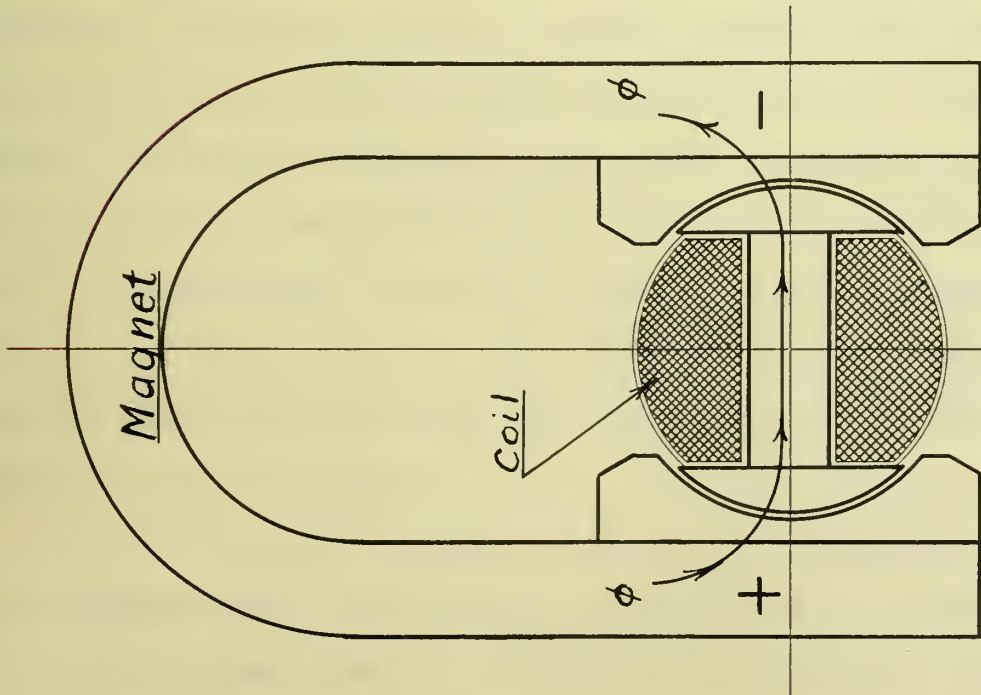
Fig. 3.

Fig. 2.

portional to the number of coil turns and to the rate of magnet-
ic change.

The permanent magnet represents a constant magneto-
motive-force that fills all the space surrounding it with lines
of magnetic force or flux, that pass from the north to the south
pole. These lines complete themselves through the magnet itself.
Outside of the magnet, they will be distributed in proportion to
the relative permeabilities of the paths possible and since
iron has a far greater permeability than has the surrounding air
or other structural material, it is evident that most of the
flux will take the iron path. All the flux taking the iron
path is the active flux, while the rest is stray field.

Starting with the armature in the position of Fig. 2,
the permeability of the iron path is a maximum so that the flux
passing through the coil is at its maximum, and the stray field
therefore a minimum. As the armature changes toward the posit-
ion of Fig. 3, the permeability decreases with a corresponding
change from active to stray field, that, slight as it is over
a wide range in the neighborhood of the position of Fig. 2, an
e.m.f. is generated. Over this range however the magnetic den-
sity of the flux is so low that tendency is to increase in
density rather than to take the stray path, so that the e.m.f.
at first is very slight.

But as the armature advances, the advancing tips of
the armature faces are creating by-passes of decreasing reluct-
ance, until finally when it reaches the position of Fig. 4,
the by-pass permeability is increasing so rapidly at the ex-
pense of the path through the coil, that the flux is drawn out

of the coil very rapidly and results in a high e.m.f. being
generated. The maximum e.m.f. under ideal conditions is gener-
ated when the armature reaches the position of Fig. 3. For
the next quarter turn the phenomena revert with the result
that the e.m.f. drops off from its maximum in the same manner
as it had risen during the first quarter turn. The two illust-
rations represented in Fig. 4 and Fig. 5 show the critical
positions of the armature during which the maximum flux changes
begin to occur and in the neighborhood of which the maximum
resulting voltage changes occur. The angle between these two
positions is relatively a small part of a complete revolution
so that the e.m.f. wave resulting from such a machine it is
evident will be of a very peaked nature.

This angle is a measure of the amount of armature
surface that bridges the pole pieces, the path represented by
which should be sufficient to carry all the flux without creat-
ing too great a magnetic density at the tips. Its amount is
also influenced directly by the active machine depth, so that
for extremely peaked open circuit voltage waves, a very deep
machine would have to be made.

As an illustration of the manner in which e.m.f. is
generated in the coil, an oscillogram was taken from the magneto
and represents both a qualitative and quantitative analysis of
the open circuit operation of the machine for the speed at
which the armature was rotating.

The oscillogram is taken by connecting a galvanometer
of the oscillograph in series with a non-inductive rheostat of
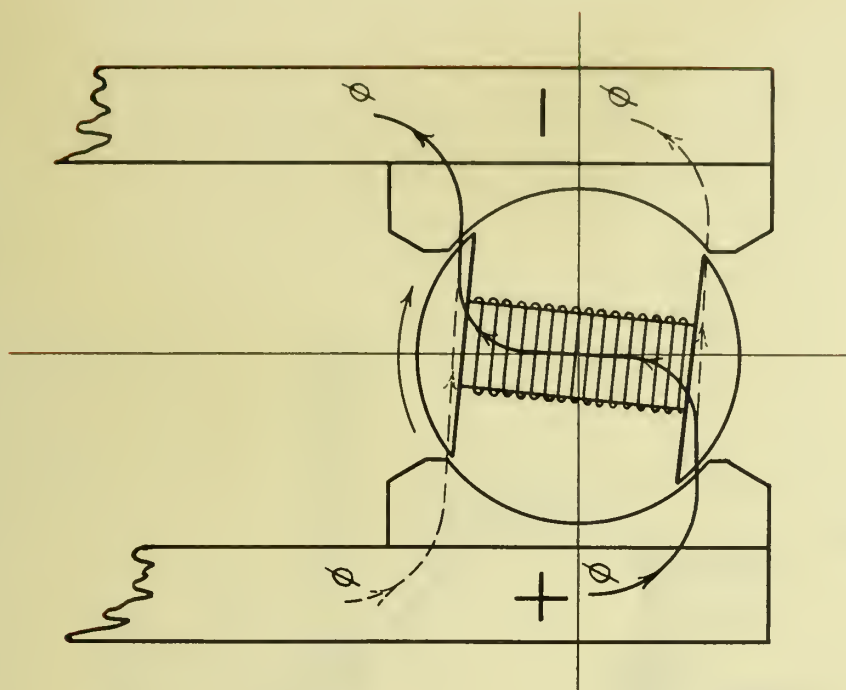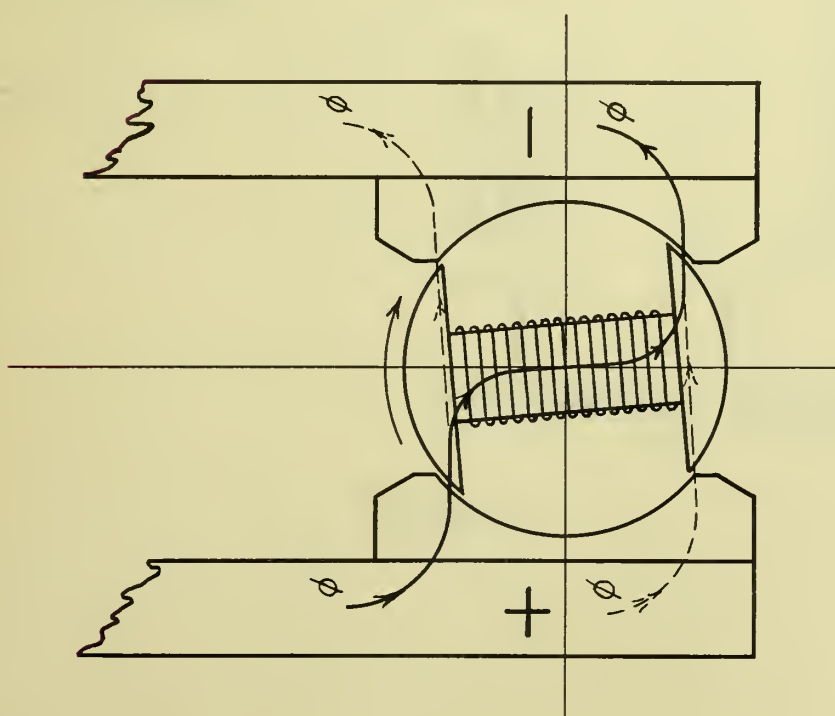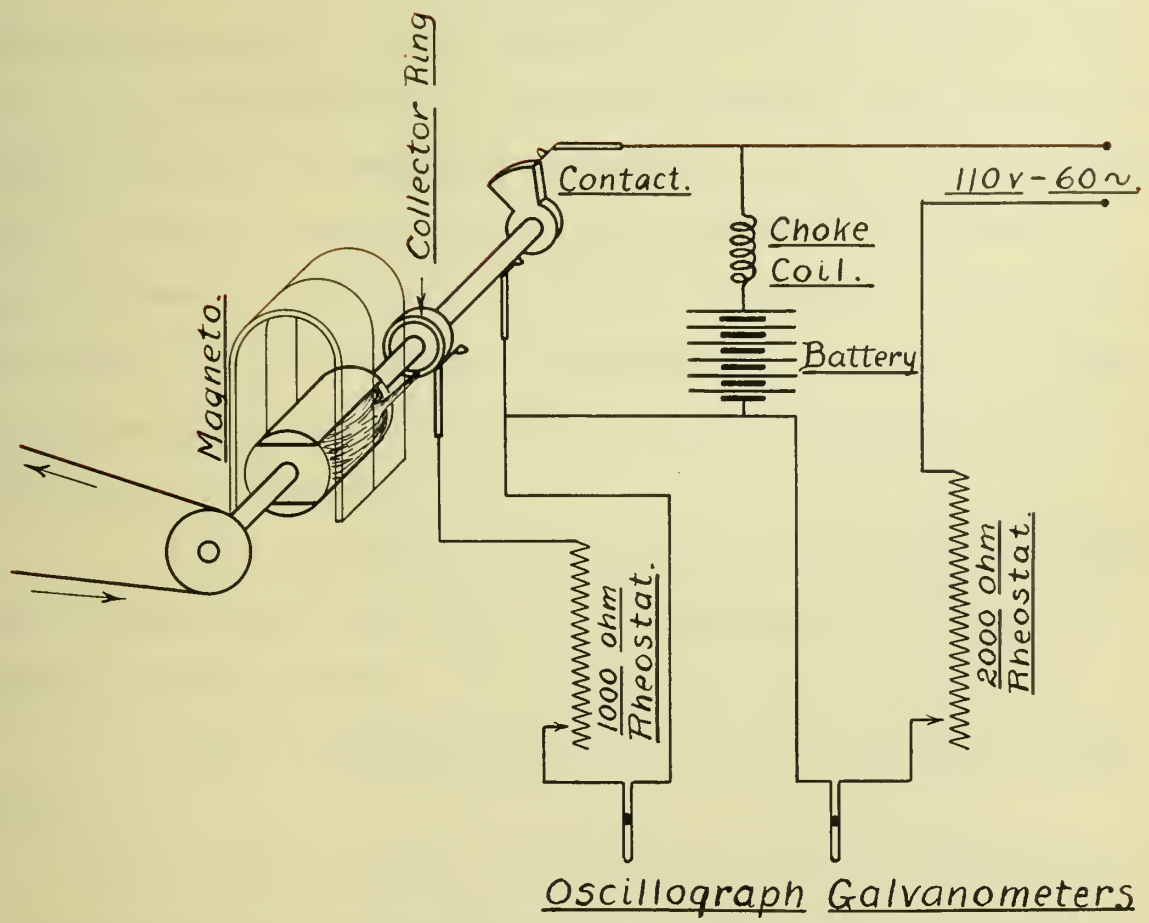about 1000 ohms resistance, directly across the terminals of

Fig. 5.

Fig. 4.

Fig. 6.

the magneto. The film was rotated at approximately the same
speed as the armature so that one complete cycle of the perform-
ance was recorded.

Together with the magneto open circuit wave, a 60
cycle voltage wave was also recorded so that a time calibration
of the record was established.

In order to fix the armature position relative to the
field pole pieces, so that the wave could be interpreted with
respect to such position, a rotating make and break contact was
driven directly connected to the armature shaft and the contact
made to break a battery and coil circuit at a time when the
armature was in the position represented in Fig. 3. The result-
ing inductive kick voltage was superimposed upon the 60 cycle
timing wave and marks the verticle line indicated in Fig. 7 by
"vertical ℄ of magneto".

The illustration Fig. 6 shows the electrical connect-
ions together with the mechanical arrangement necessary for
making the above test.

Fig. 7 represents the recorded open circuit voltage
wave.

A study of this oscillogram shows that the wave was
a decidely peaked one and that the maximum voltage reached was
53.2 volts. For an accurate determination of the speed at which
the armature was rotating for this cycle, it is only necessary
to compare it with the 60 cycle timing wave. Such a comparison
shows that the armature speed was 601 r.p.m. The arrow shows
the sequence of events along the card.

It will be seen that the maximum voltage occurred

Fig. 7.

shortly after the time at which it was predicted to occur under ideal conditions. The slight distortion in the actual wave form is due to the iron losses that are present for this particular speed of operation. Perhaps a part of the distortion can be attributed to the effect of the small current taken by the oscillograph galvanometer. The effect of the galvanometer current was reduced to a minimum by having the series resistance as high as possible.

The law that defines the electro-magnetically generated e.m.f. unit states that one volt of e.m.f. is generated at the terminals of a coil, if a magnetic field, interlinked with the coil, changes its interlinkage at the rate of 100,000, 000. or 10^8 turn-maxwells per second. This law can be expressed mathematically by

$$E = \left(\frac{N}{10^8}\right)\frac{\delta\emptyset}{\delta t}$$

where "N" represents the number of turns in the coil, "$\emptyset$" the excitation flux and "t" time.

By the use of this equation and the data represented in the oscillogram Fig. 7, it is possible to calculate the amount of active flux involved in the performance of the magneto and the rate at which the magnetic changes occur with any particular change of the armature. Such a calculation made from this oscillogram gives the total flux represented as about 35,000 maxwells. The maximum rate of magnetic change was about 7,100,000 maxwells per second. It is evident that the study of the open circuit operation of the magneto affords a very good method of studying the flux output of magnet bars.

In the above discussion of open circuit operation, constant speed of armature rotation was assumed and the oscillographic analysis made at one particular speed. The effect of speed upon the voltage generated by the magneto is a very important consideration. Judging from the above e.m.f. equation, one is led to beleive that the voltage would increase directly in proportion to the speed increase, and it would under ideal conditions, but as the speed increases, the magnetic changes in the iron path also increase, with the result that the iron losses become of considerable moment. A speed will eventually be reached where no increase in e.m.f. will result from increased speed; i.e., the machine approaches the constant effective e.m.f. condition with increased speed. However over the ordinary speed range at which the magneto is called upon to operate, the deviation from the law expressed in the above equation is only very slight.

Tests of the speed-e.m.f. relation are usually taken by measuring the open circuit voltage with a high resistance alternating current voltmeter at different armature speeds over the speed range desired. Such a test of this magneto is represented in the data tabulated as follows,

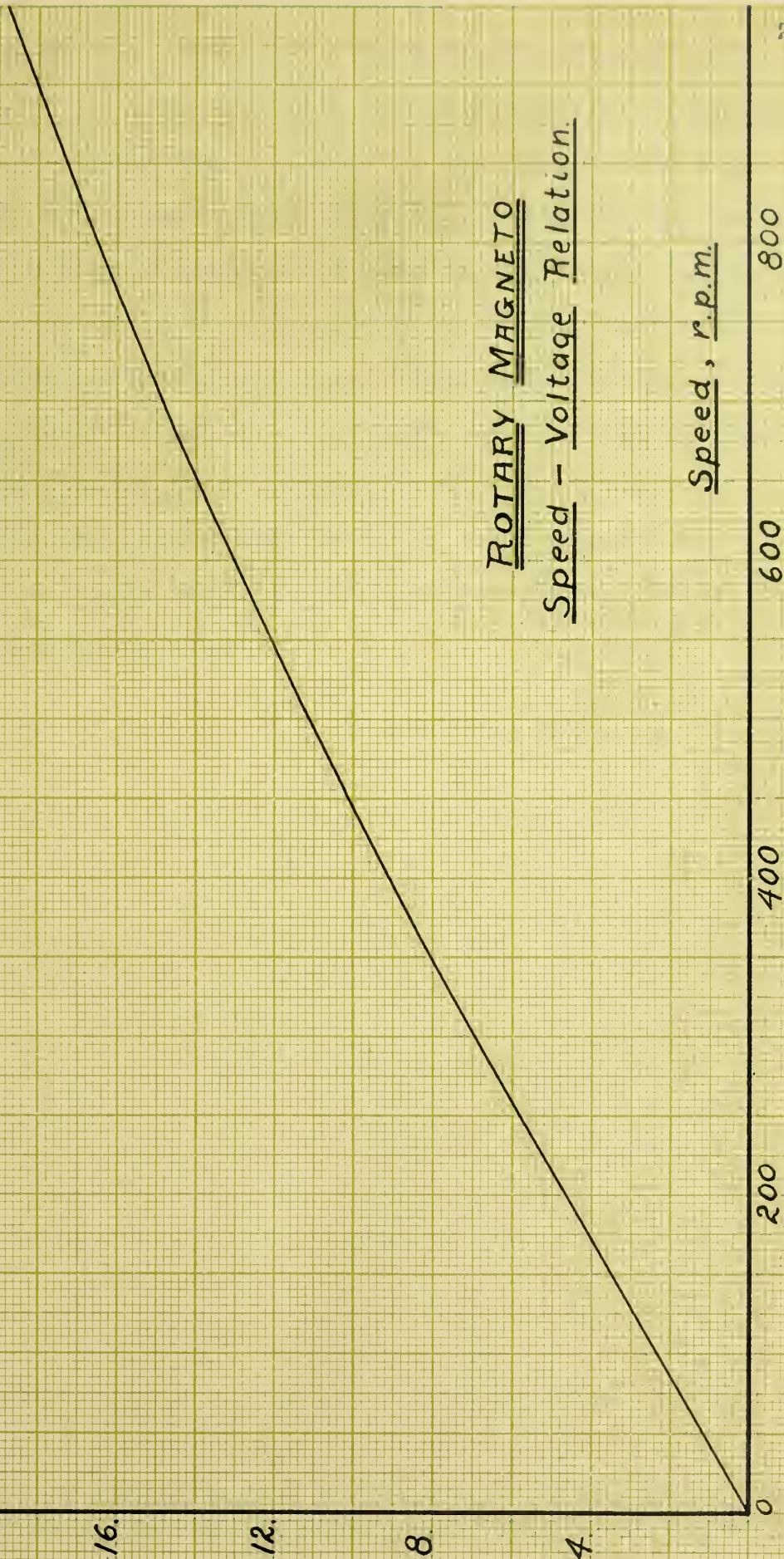| R. P. M.	E. M. F. (eff.)
212	4.9
356	8.2
508	11.3
676	14.4
812	16.7

The above data is plotted to scale in the diagram represented in Fig. 8.

Had it been possible to obtain a voltage wave under

ROTARY MAGNETO
Speed – Voltage Relation.

Speed, r.p.m.

Fig. 8.

Eff. E.M.F., volts.

ideal conditions, i.e., free from the distortion caused by iron losses, there is no doubt but what the maximum e.m.f. reached would have been higher than is shown in the oscillogram Fig. 7. The effect of iron losses tends therefore to flatten the wave, so that for the higher speeds, the open circuit wave form will be quite different from that for low speeds, with the result that the maximum instantaneous e.m.f. increase with the increased speed will be less than the effective e.m.f. increase. When it is realized that at about 600 r.p.m. the maximum e.m.f. generated was only .0886 volts per turn, it is evident why it is impossible to build high tension magnetos without using the inductive transforming principle.

CHAPTER IV.

SHORT CIRCUIT OPERATION.

Consider next that the coil is short circuited and that the armature is rotated at some constant speed. The e.m.f. generated will cause current to flow that will be limited in its amount by three conditions, the resistance of the coil, the inductance of the circuit and the armature reaction.

There will be a difference in wave shape and in the phase relation with respect to armature position, between the e.m.f. generated during short circuit and that of open circuit. This difference is caused by the effect of the armature reaction and its general action can be described as producing a more evenly distributed rate of flux shift than occurs during open circuit.

The current that causes this armature reaction is delayed in its response to e.m.f. changes by the inductance, so that it is evident that there will be a difference both in phase relation and in wave shape between the short circuit current and the impedance e.m.f. waves, and therefore a still greater difference between the open circuit e.m.f. wave and the short circuit current waves. The amount of this difference will be apparent later in the discussion.

The effect of the resistance is well known for it is always in phase with the current causing it.

The following diagram Fig. 9 shows the relation between the excitation and the reactive magnetic forces for a position of the armature where the current is rising very rapidly toward its maximum value. At this position the current has reached about one half of its maximum.
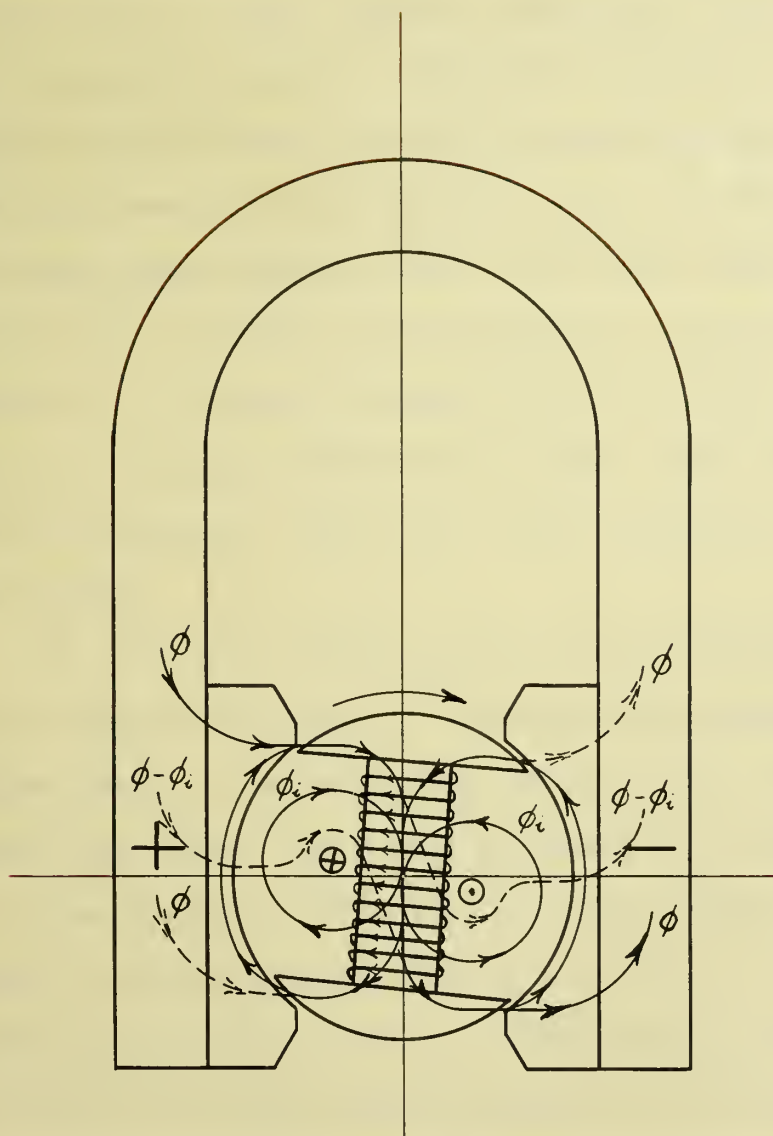
Fig. 9.

This position of the armature is approximately the position of firing for the running condition of the engine, or the so called "advanced" position.

The fundamental reason for the difference between the action of the magneto on open circuit and that on short circuit is that no electrical energy can be generated on open circuit and that on short circuit the energy generated is a maximum. The uneven manner in which the magnetic changes are affected for the different armature positions makes the energy generated for some positions greater than for others, and since all the energy generated for each revolution must be consumed by the resistance during that revolution, it is evident that there will be a storage of energy, during the armature posit- ions where the energy generation is great, that will be given up when the generation falls off. This condition is known as an energy surge.

In Fig. 9 it will be seen that the reactive flux opposes the excitation flux at the advancing armature tips and aids at the leaving armature tips, so that the tendency is to retard the flux change from what it would be on open circuit. This is in accordance with Lenz' law, which states that every phenomenon in nature sets up forces that tend to oppose the forces producing it. The action of the adding forces at the leaving tips tend to pull harder against the rotation of the armature on short circuit than is true for the same position during open circuit, accounting for the additional mechanical energy required.

The flux change at any instant therefore becomes the difference between the excitation and the reactive fluxes,

when considered in respect to the natural open circuit change
for the same instant or armature position. It must be borne in
mind that there is no neutralization of flux and that the same
total amount of flux is changed with respect to the coil on
short circuit as on open circuit, the difference being in the
rate of change for corresponding armature positions.

By a comparison of the flux diagrams for open circuit
and short circuit condition, it will be seen that if a sudden
change were to occur from the short circuit to the open circuit,
the resulting stored energy dissipation in an arc would be, not
alone the effect of the sweeping out of the reactive flux, but
of the sweeping back of the excitation flux to the natural path
from which it had been held during short circuit, so that the
phenomenon of sparking in the case of magnetos is a double
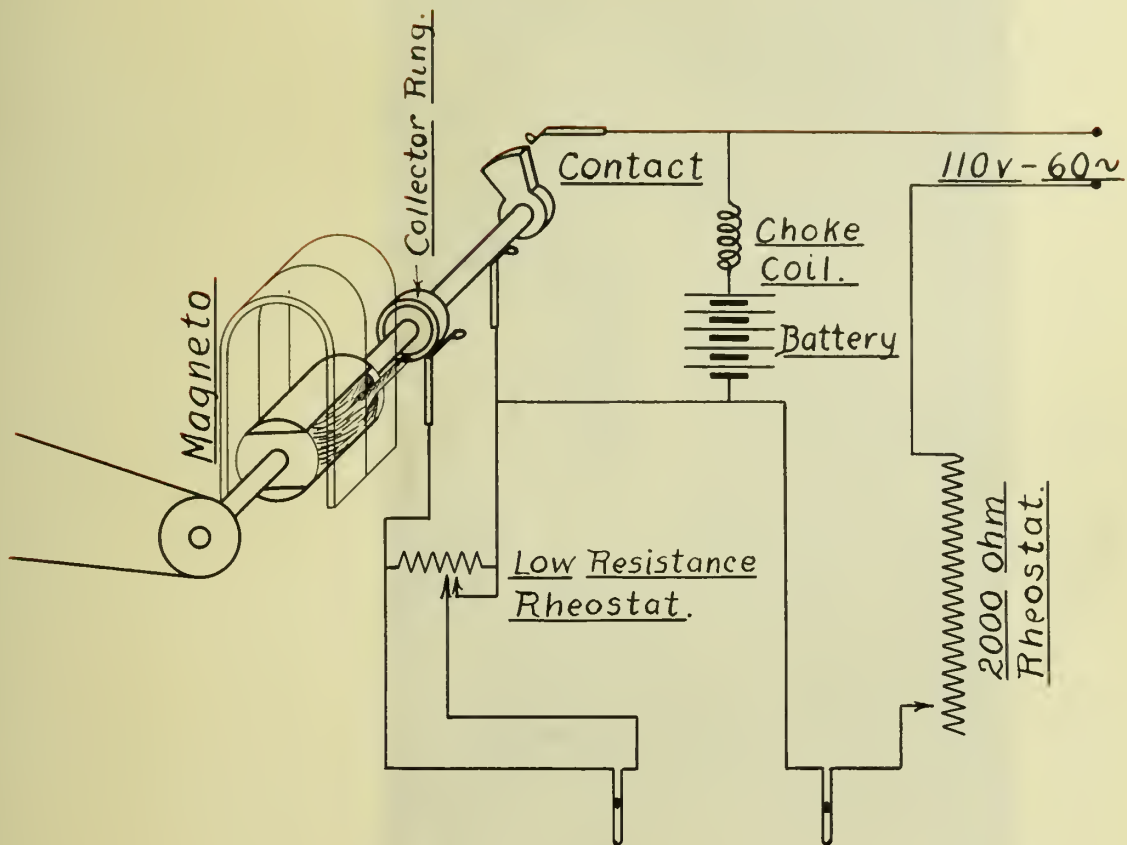magnetic one.

In order to obtain a record of the current wave of
this magneto, under conditions approaching as near as possible
those of short circuit, the magneto was connect across a low
rheostat. The oscillograph galvanometer alone was connected
across this rheostat and the set up adjusted so that the resist-
ance in series with the magneto was as low as possible and still
give a galvanometer deflection of good amplitude. The resist-
ance of this rheostat was only a fraction of an ohm, so that
the effect upon the current output was only very slight.

Arrangement was also made for indicating the armature
position with reference to the wave received, in the same man-
ner as in the open circuit voltage test.

The mechanical arrangement together with the electric-
connections are shown diagrammatically in Fig. 10.

Collector Ring.

Magneto

Contact

Choke
Coil.

Battery

110v – 60∿

Low Resistance
Rheostat.

2000 ohm
Rheostat.

Oscillograph   Galvanometers.

Fig. 10.

Fig. 11.

Fig. 11 is a representation of the oscillogram illust-
rating the short circuit output of the magneto for one complete
revolution of the armature.

A study of the above oscillogram shows that the max-
imum current value reached during the cycle was 1.017 amperes.
The current rose very rapidly from zero toward its maximum and
after maintaining a relatively high value over quite a range
of armature positions it gradually decreased to zero. The gen-
eral effect is a broad flat current wave and from it a wide
energy range would be expected. A comparison with the 60 cycle
timing wave shows that the armature was rotating at a speed of
628 r.p.m. at the time the oscillogram was taken. The relative
position of the armature with respect to the pole pieces is
also designated in this card in the same manner as in Fig. 7
and shows that the current was approximately at zero for the
position of Fig. 3.

A study of the wave shows further that the current
reached its maximum at about 60 degrees of armature position
after the time of zero current and by comparison with the open
circuit voltage wave of Fig. 7, it is seen that the current .
maximum occurs about 50 degrees later than the open circuit
voltage maximum. This difference in phase means very little
because of the wide difference in the two wave shapes. During
the first 15 degrees after the position of zero, the current
rose very rapidly to almost its maximum.

Fig's 7 and 11 represent the operation of the magneto
under its two extreme conditions. The current that would be
drawn from the magneto by some external circuit would change
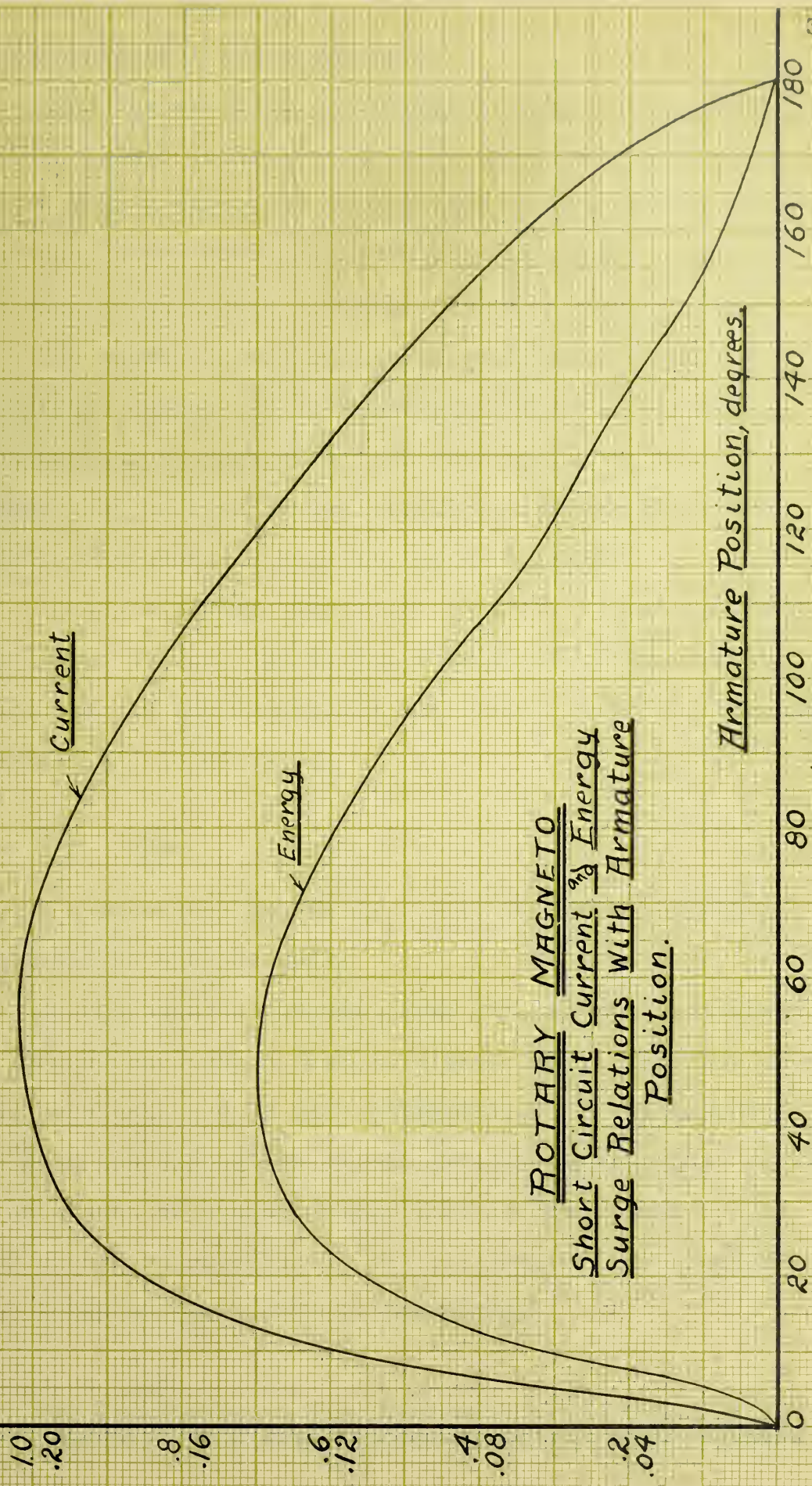the wave shape materially, but it would be somewhere between the
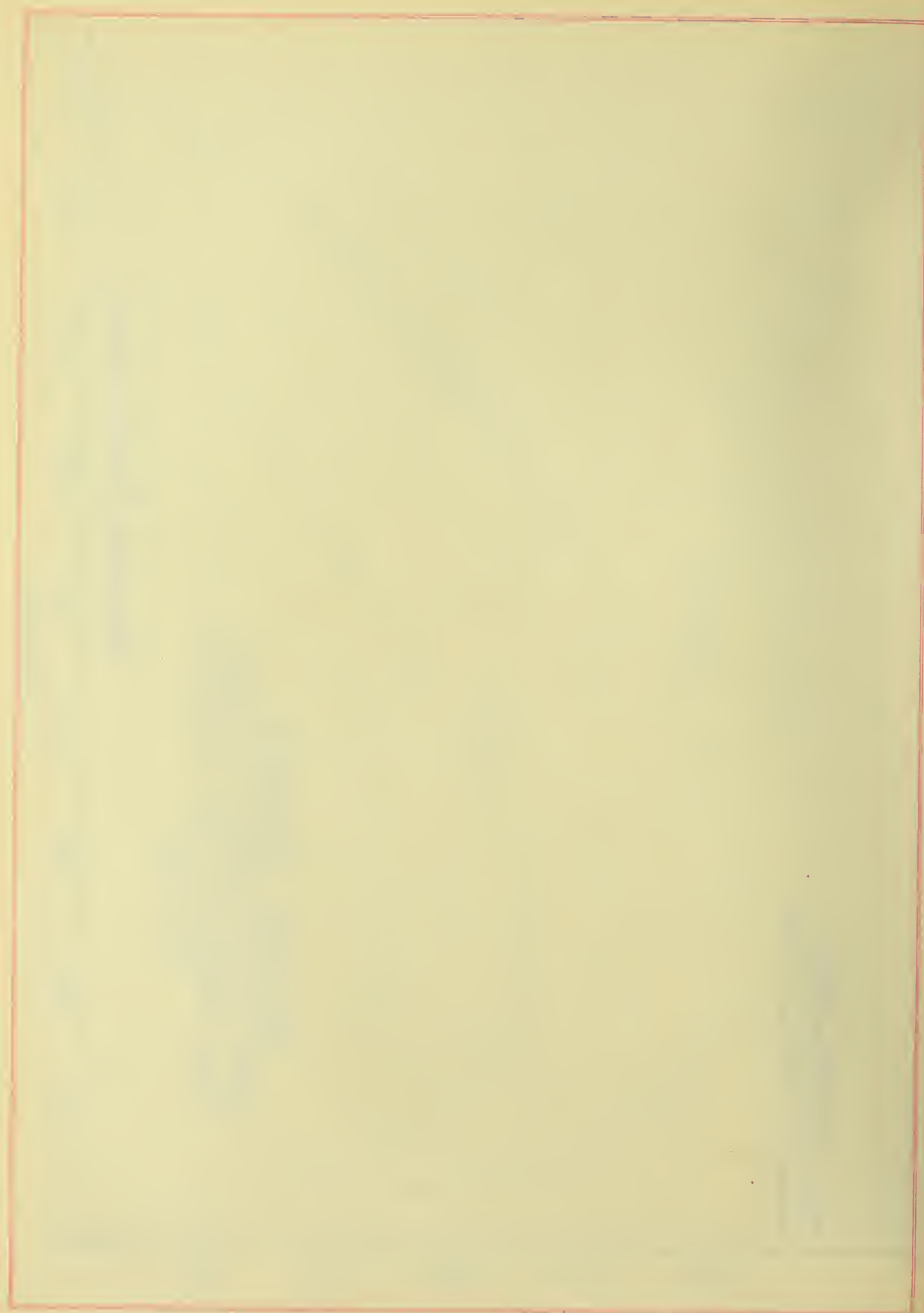
Rotary Magneto

Short Circuit Current and Energy Surge Relations With Armature Position.

Fig. 12.

waves represented for these extremes.

From the short circuit current wave and the relation between the circuit inductance and the armature position, it is possible to make a tabulated calculation of the impedance e.m.f. wave, but due to the uncertainty of the inductance relation shown in Fig. 1, this wave determination will be omitted.

The short circuit operating condition is that of maximum current output and consequently the condition under which the maximum storage of energy will occur, so that it is of interest that an idea of the stored energy, resulting from the current wave shown in Fig. 11, be calculated.

In the ordinary electrical circuit, it can be shown that the energy stored, due to the inductance of the circuit, is proportional to the inductance and to the square of the current flowing, and is of value,

$$W_L = \frac{Li^2}{2}$$

This amount represents the energy due to the interlinkage of the reactive flux and the coil.

In the magneto however, each line of reactive flux holds a line of excitation flux in a path that is not its natural one, considering only pure permeability of the magnetic path, so that the distortion of the excitation flux must represent an amount of stored energy that is just equal to the amount of energy represented in the presence of the reactive flux. The total stored energy is therefore,

$$W = Li^2$$

By using this equation in connection with the data

ROTARY MAGNETO

Speed – Short Circuit Current Relation

Fig. 13.

Speed, r.p.m.

Eff. S.C. Current, amps.

available in the curve of Fig. 1 and the oscillogram of Fig. 11,
the value of the stored energy for different armature positions
is obtained. Such a calculation was carried out and the results
plotted to scale as is shown in the diagram Fig. 12. This dia-
gram also has the current wave of Fig. 11 reproduced upon it
so as to illustrate the difference between the current wave
and the resulting energy surge accompanying it.

The uncertainties existing in the correctness of the
curve of Fig. 1 will of course produce errors in the energy
calculations. However, since the energy value depends upon the
value of the current squared and upon only the first power of
the inductance, the error resulting will not be very great.
From this curve it will be seen that the maximum value of energy
stored during the surge was .14 joules, and it is further evid-
ent that the stored energy range is not as wide as the short
circuit current range.

The variations of the short circuit current output
from the magneto for the different operation speeds is of great
importance. For increases in speed, the tendency is for a higher
value of impedance voltage generation at any instant and there-
fore a higher current value, but for the higher frequency of
current alternations, the current changes are more rapid and
the consequent inductive effects more pronounced, so that at
a very low speed in magneto practise, the increased impedance
e.m.f. due to increased speed is entirely consumed by the induced
e.m.f. with the result that the current maintains a constant
root-mean-square value. In general, it is the aim of designers
of magnetos to have the current reach its r.m.s. constant value

at about the running speed of the engine. In cases, where
starting of the engine is desired directly from the magneto,
it is advantageous to have the current reach its constant value
at an earlier speed. The speed-current characteristic of the
magneto is adjusted very easily by merely changing the number
of turns put into the coil. In general, magnetos wound to
facilitate starting are wound with many turns of fine wire.

Fig. 13 represents the relation between the armature
speed and the effective current output over a range of from
zero to 1000 r.p.m. and shows that the current increase was
only very slight after 400 r.p.m.

CHAPTER V.

SPARKING PHENOMENA.

The breaking of an electro-magnetic circuit is equivalent to the insertion of an added variable resistance. If the circuit contains energy stored in the form of a magnetic field, then at the time of break, most of the energy will be dissipated at the gap in the form of an arc of heat.

The amount of this energy will be of the form,

$$W_s = \int_0^t i^2 r_s \, \delta t$$

where "i" and "r_s" are both functions of "t" during the period of sparking. But the potential drop across the spark points at any instant is,

$$e_s = i r_s$$

so that the energy of the spark can be expressed by,

$$W_s = \int_0^t e_s i \, \delta t$$

In this equation "e_s" and "i" are also functions of "t". The equation is now in its best form for application, because it is possible to determine the relations between "e_s" and "i" with "t" for an ignition spark, by means of the oscillograph, and the value of "W_s" is therefore readily obtainable.

On short circuit it was shown that an amount of energy of value,

$$W = Li^2$$

is stored in the circuit, available for an ignition spark.

When the circuit is suddenly broken, most of the energy is dissipated in the spark in the form "W_s" already

shown. Some of the energy however is lost in the iron due to the sudden magnetic shift that occurs, and some of the energy will be lost in the resistance of the coil. During the period of sparking, the continued motion of the armature adds some energy to the circuit. In a simple electro-magnetic circuit it can be shown that the energy added during sparking, due to the closed circuit condition existing through the spark, is just equal to the copper losses of the coil. It will be assumed that the same is true in the case of magnetos. Therefore if the iron loss energy is designated by "W_f", the following equation holds true for the principle energy amounts involved during the phenomena of sparking.
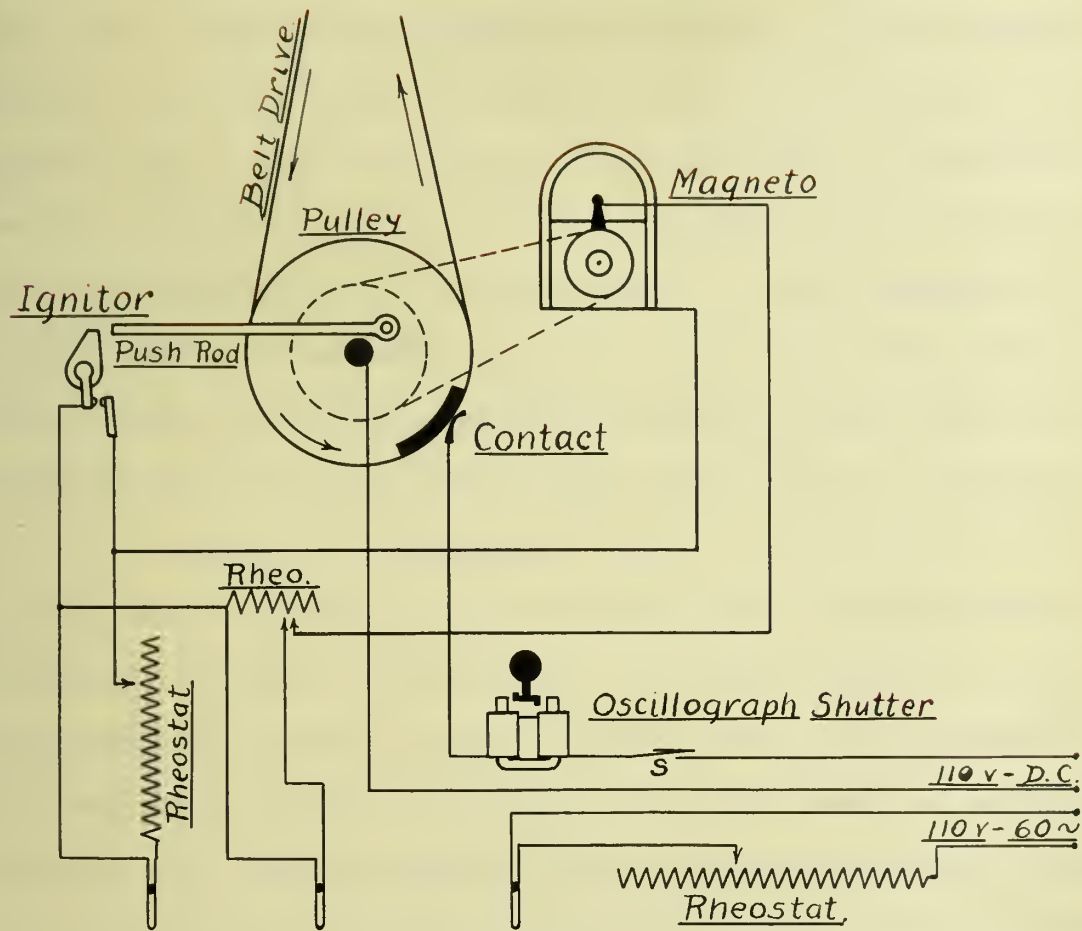
$$W = W_s + W_f$$

From the above equation it is evident that any method that makes it possible to measure the current-time and the spark-gap voltage-time relations during the period of sparking, makes it possible to determine the amount of energy represented in the spark. An method that makes it possible to determine the value of current at the instant just before break, makes it possible, by the use of the value of the coefficient of self-induction for the same armature position, to determine the amount of stored energy. The value of the iron losses coincident to sparking can therefore be ascertained by the difference as per the above equation.

To make these determinations by means of the oscillo-graph, it is only necessary to connect one of the galvanometers in series with a high resistance across the the spark points, for the sparking voltage determination; another galvanometer across a low resistance rheostat in series with the circuit, for

Oscillograph Galvanometers.

Fig. 14.

current determination and the third galvanometer to an alter-
nating current supply circuit of known periodicity for time
calibration. In order that the phenomena be stretched out on
the resulting oscillogram, so that time measurements can be
made with a reasonable degree of accuracy, it is necessary to
operate the film drum at as high a speed as is possible without
danger of too little exposure of the film and a resulting faint
record. A speed of 1000 to 1200 r.p.m. for a General Electric
Co. oscillograph film drum is suitable in the measurement of
current and voltage changes that occur in the brief periods of
time in which sparking phenomena complete themselves. The record
however will be too faint to print from without retracing.

There is no doubt but what the connections of the
galvanometer circuits to the magneto alter the conditions to
a certain extent, but the amount of energy required by the
galvanometers is very slight compared with that represented in
the magneto so that their effect will not cause any serious
error in the results received. The best way in which to judge
the effect of these measuring circuits is by a visual inspect-
ion of the spark received both with and without the extra
circuits attached. When it is realized that an average spark
will have a power of from 40 to 60 watts it is evident that
the galvanometers can have only a slight effect. Calculations
will be presented later in connection with the actual measure-
ments of spark energy amounts to show the amount of error that
is produced by these measuring conditions.

Fig. 14 represents the mechanical arrangement and the
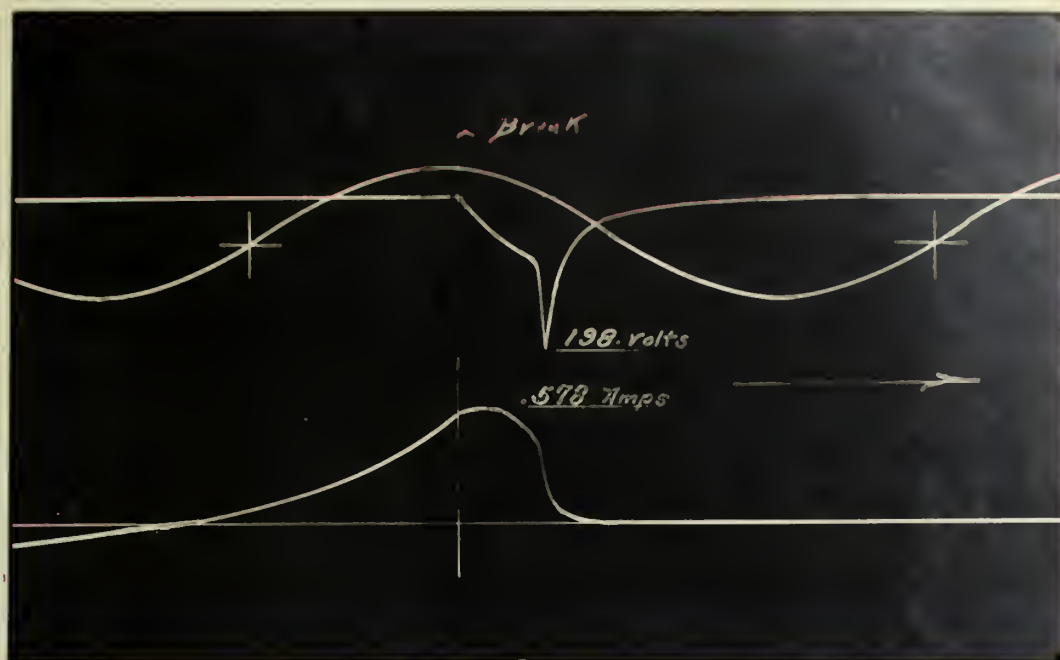electrical connections, in a diagrammatical way, for determining

the current and voltage changes in a magneto during sparking.
In this diagram, a pulley rotating about 300 r.p.m. drives a
magneto through a chain belt at twice its speed. This pulley,
by means of an eccentric push rod, operates an ordinary make
and break ignitor plug, that can be set to make and break the
magneto circuit at any desired armature position. Because of
the fact that the magneto is chain driven by the pulley, the
circuit is always broken for the same armature position. Mounted
on the driving pulley is a contact that is set to complete the
oscillograph shutter circuit at a time when the spark is occurr-
ing at the ignitor points. This contact affords time for one
complete revolution of the oscillograph drum at a speed several
times that of the pulley. In order to control the oscillograph
shutter circuit manually, a press key "S" is also inserted in
the circuit.

In order to obtain a quantitative idea of the sparking
range of the magneto in terms of thermo-electric heat units,
oscillograms recording the current and voltage time relations
during sparking were taken for five different armature positions.
The following illustrations represent these oscillograms, Fig's
15, 16, 17, 18, and 19.

These oscillograms show not only the maximum value
from which the current dropped, but the general manner in which
in which the drop took place, and the time required. The nature
of the current sustaining e.m.f. is also apparent. Especial
attention is called to the fact that the e.m.f. does not reach
its maximum until very late during the life of the spark and as
will be shown later at a time when the energy has been nearly
all dissipated. In the oscillogram Fig. 15, which was taken at

Armature at 10°.

Fig. 15.

Armature at 40°.

Fig. 16.

1.012 Amps   174.3 volts
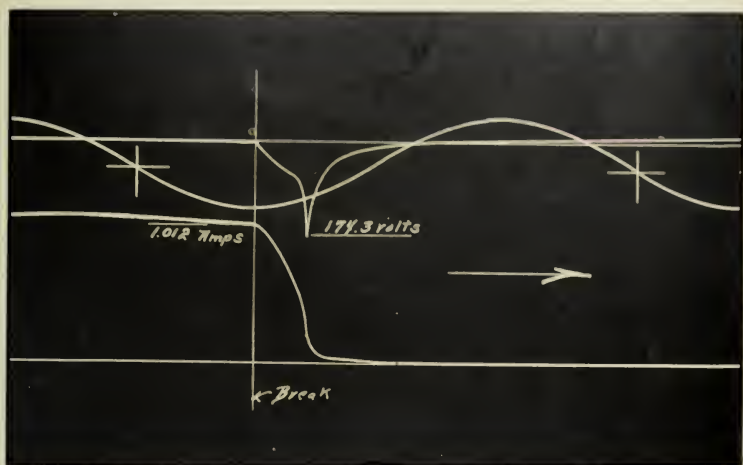
←Break

Armature at 70°

Fig. 17.

←Break

172. volts

.877 Amps

Armature at 100°

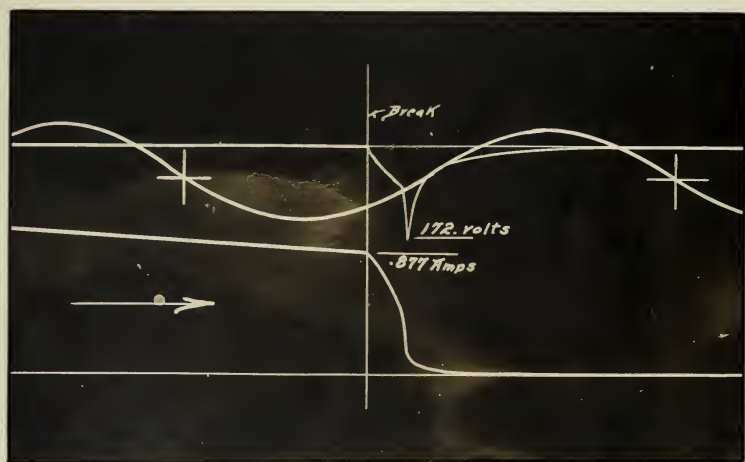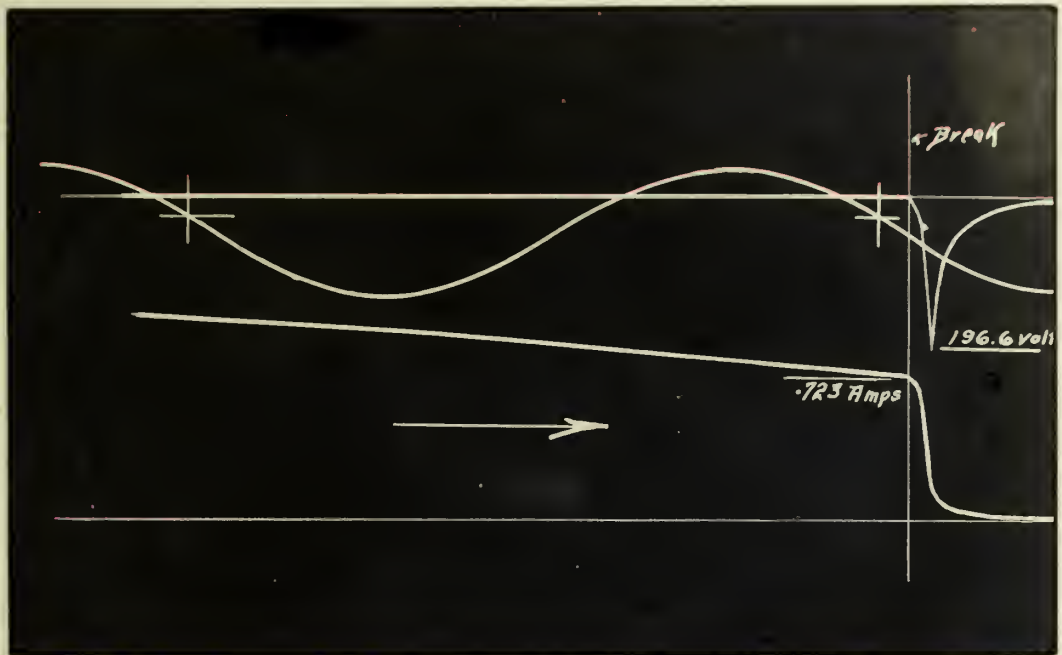*Fig. 18.*

Armature at 120°.

Fig. 19.

a time when the current was rising very rapidly, it will be noticed that the current even rose slightly after the break had begun. This was caused by the fact that the added gap resistance due to break was not sufficient at first to check the electrical acceleration.

To illustrate the method of calculating the spark energy and the energy lost in the coil copper, the data available from the oscillogram Fig. 16 will be taken as a basis of sample calculations. This particular case was taken as it represents the hottest spark.

In the following tabulation is shown the measured current-time and the voltage-time relations, and together with them is the power-time relation obtained by multiplying the simultaneous current and voltage values. It is also possible to calculate the spark resistance for the same instances but they will not be included in this paper.

t seconds	i amperes	e_s volts	P_s watts
.0000	1.066	.00	.00
.000191	1.047	14.95	15.65
.000381	1.018	24.90	25.35
.000571	.970	34.85	33.80
.000762	.931	42.30	39.40
.000952	.864	49.80	43.10
.001143	.806	54.80	44.20
.001333	.739	62.20	46.00
.001524	.672	69.70	46.80
.001714	.605	74.70	45.20
.001905	.509	84.60	43.10
.002095	.423	94.60	40.00
.002285	.192	122.00	23.41
.002476	.096	127.00	12.20
.002666	.0576	92.10	5.30
.002857	.0384	69.70	2.68
.003100	.0288	54.80	1.58
.003430	.0240	34.85	.83
.003810	.0192	24.90	.48
.004190	.0144	19.90	.29
.004570	.0096	14.94	.14
.005330	.0000	9.96	.00

From a study of the above tabulation, it will be seen that the maximum power of the spark reached was 46.80 watts. The current dropped from the value of 1.066 amperes to practically zero in approximately .00533 seconds. While this period represents the total spark duration, it will be observed that the most of the energy had been dissipated in less than half that time.
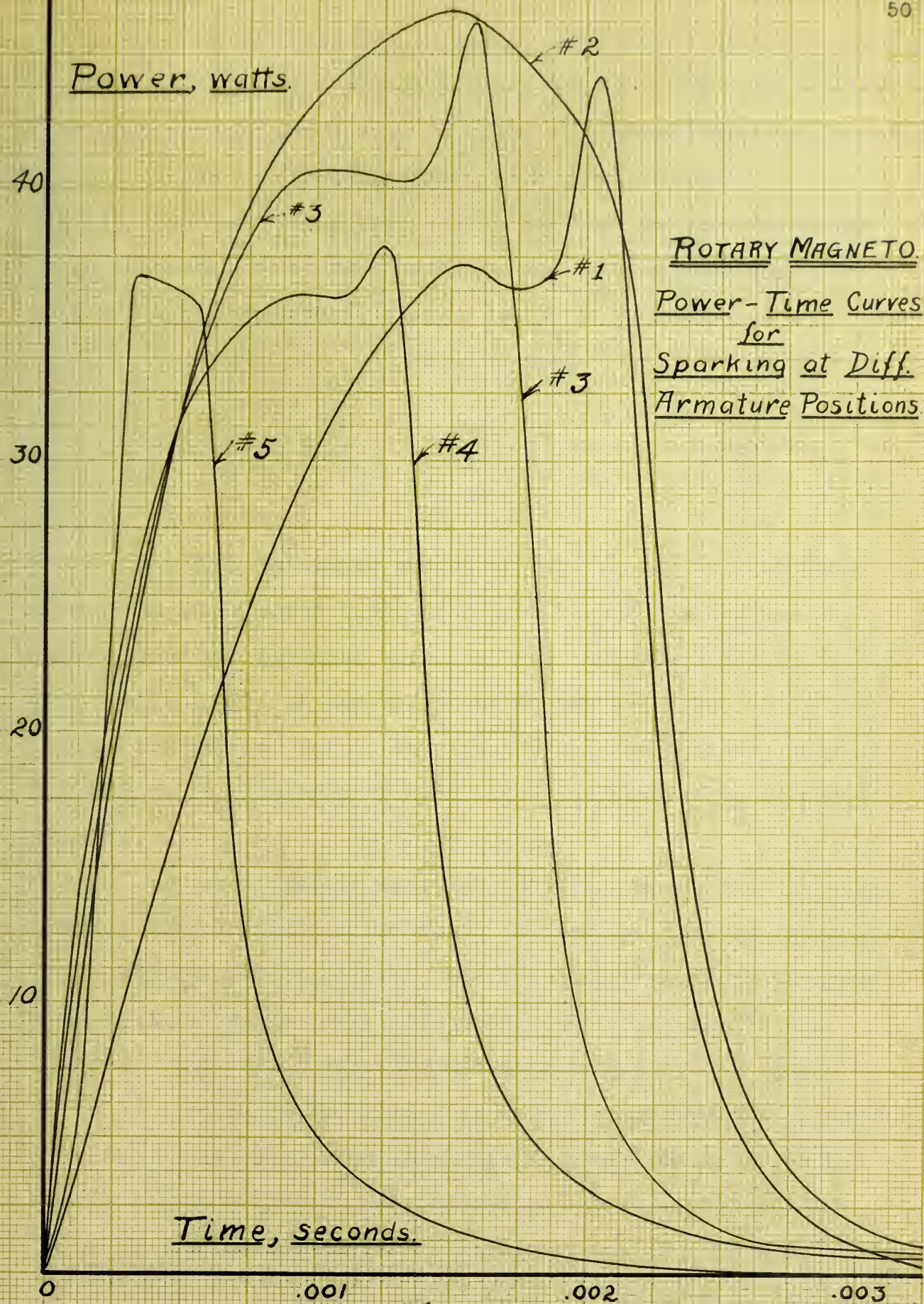
At a time .001524 seconds after break, when the spark power had reached its maximum of 46.80 watts, the current value was .672 amperes and the induced voltage 69.70 volts. The resistance of the spark therefore for that instant is obtained by dividing 69.7 by .672. This gives the ohmic resistance of the spark as 103.6 ohms. The shunt resistance in series with the galvanometer for voltage determination was approximately 1000 ohms so that it is evident that the current taken by the oscillograph was only about .10 of the spark current. For instances earlier during the period of sparking the percentage is much less. The effect of the galvanometers therefore cause little error in the determination of the spark energy, but there is no doubt but what they have considerable effect upon the spark at the time when the voltage is at its maximum and the energy very small, so that the maximum e.m.f. during sparking will no doubt be considerable in error.

Like power-time relations were calculated for all the five sparks measured and all are plotted to the same scale as per curves in diagram Fig. 20.

The area enclosed by these curves and the zero power line is a direct measure of the energy represented in each, so

Fig. 20.

ROTARY MAGNETO.

Power-Time Curves for Sparking at Diff. Armature Positions

that it is only necessary to measure the area enclosed by each
curve, by means of a planimeter and multiply the area received
in each case by the energy represented per unit area as is deter-
mined by the co-ordinates used. Such a measurement of the curves
gives the following energy values for the sparks. The sparks
are numbered in the same order as the oscillograms Fig's 15 to
19 inclusive are presented.

Spark #	Total Energy, joules.	Effective Energy, joules.
1	.06585	.0497
2	.08950	.0770
3	.06690	.0557
4	.04720	.0346
5	.02180	.0138

From the power curves of Fig. 20, it will be seen
that the spark power rises from zero toward its maximum and
then drops off again to zero, so that there is a period of time
at the beginning of the spark and at the end also, where the
power is low; too low to be effective in the ignition duty of
the spark, so that energy spent at a low power rate is wasted
energy.

For effective ignition service a spark must have an
energy delivery rate of 25 watts or over, so that an integration
of the power curves, between the time limits at which the power
was above 25 watts, will give the effective energy of the
sparks. The values received are tabulated above as shown.

To carry the energy distribution determination further
the copper losses during sparking can be determined from the
current-time relations represented in the oscillograms. The
rate of copper loss can be obtained by squaring the current for
the successive instances and multiplying by the coil resistance.

Copper Loss, watts.

ROTARY MAGNETO.

Copper Loss During Sparking.

#2.

#3.

#4.

#1

#5

Time, sec's.

Fig. 21.

An integration of the relations thus received gives the energy represented in the losses.

The rates of copper loss for each of the sparks are plotted to scale in the diagram Fig. 21.

An integration of these curves gives the following results.

Spark #	Copper Loss, joules.
1	.002395
2	.005760
3	.004170
4	.002360
5	.000750

These amounts of energy were assumed to be replaced by the motion of the armature, during the period of sparking.

It will be well now to plot the calculated results with respect to the armature position, so as to get an idea of how the energy distributes itself during sparking for the different armature positions along the sparking range. These relations are plotted as per diagram Fig. 22, included in which is the curve representing the value of stored energy taken from Fig. 12.
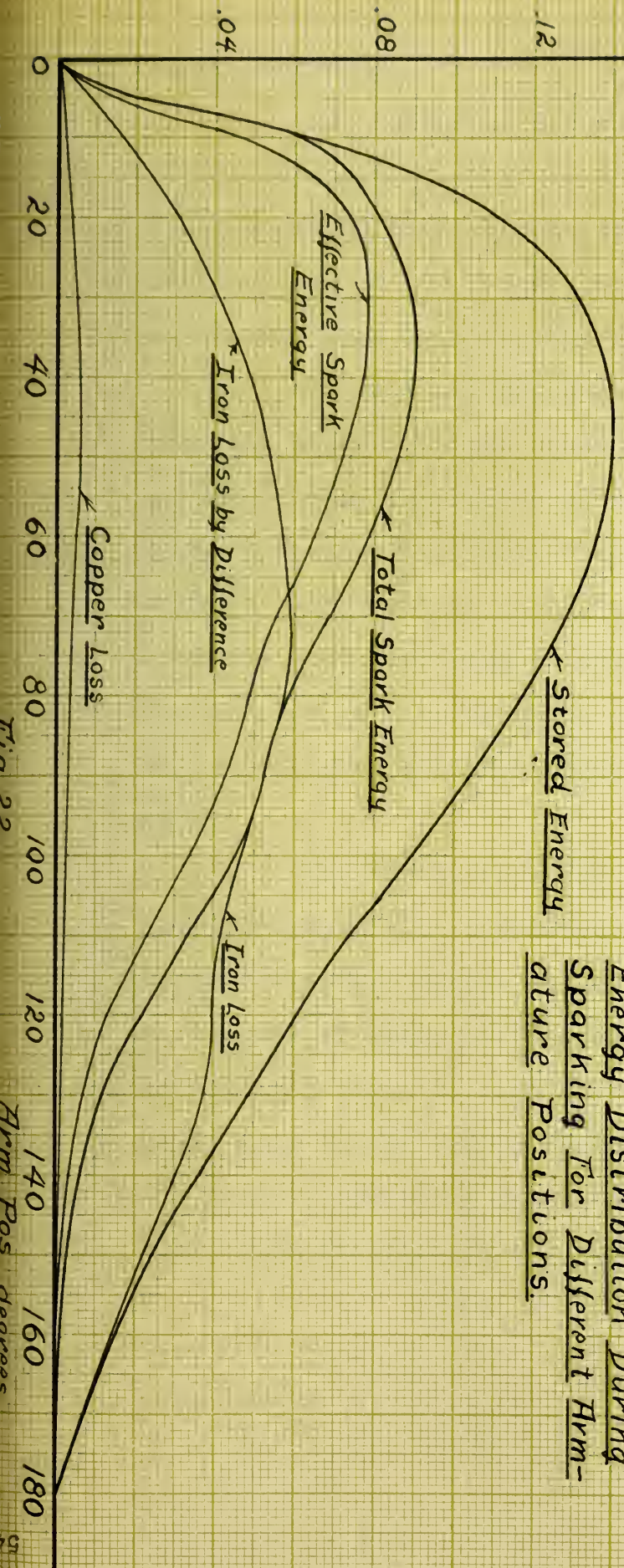
If the calculated value of stored energy were correct, it would be possible to obtain a correct valuation of the iron losses during sparking. This loss is shown in Fig. 22 but is uncertain, due to the lack of assurance in the original relation between the coefficient of self-induction and armature position. The iron loss curve does show however, that the iron loss is one of considerable moment in magneto operation. Iron loss becomes even more pronounced in high tension magnetos, due to the greater quickness with which the magnetic changes occur

Energy, joules.

Effective Spark Energy

Iron Loss by Difference

Copper Loss

Total Spark Energy

Stored Energy

Iron Loss

Energy Distribution During Sparking for Different Armature Positions.

ROTARY MAGNETO

Arm. Pos. degrees

Fig. 22

during sparking.

By a study of the curves of Fig. 22, an idea of the effective sparking range of the magneto is obtained. At the speed at which this magneto was operating, which was in the neighborhood of 600 r.p.m., it is seen that the energy receivable was fairly high over a range of about 50 degrees.

It must be remembered however that this range is received under constant speed of operation. During the process of starting an internal combustion engine, the timer is adjusted so that the spark will occur late on the piston stroke and will be received late on the magneto sparking range, where at best the energy receivable will be low. Add to this fact that the magneto will be operated at a very low speed, and the reason why starting on a rotary magneto is uncertain will readily be seen.

The manner in which the sparking ability of the magneto increases with increased operating speeds follows very closely the same manner in which the short circuit current is influenced by speed differences. This fact is considerable of an advantage both in high and low tension magnetos, because variations in the engine speed do not effect the uniformity of the magneto operating characteristics unless the speed should drop below the knee on the current-speed curve.

CHAPTER VI.
CONCLUSIONS

In the preceding chapters, an attempt has been made to show the electrical performance of the rotary magneto of the low tension type, by showing first the open circuit operation, the short circuit operation and finally the phenomena of spark-ing produced by the sudden change from the short circuit to the open circuit condition.

Before closing it will be well to consider the modif-ications necessary for producing a high tension system of the same general class of magneto.

The high tension magneto consists of a primary coil shorted through a mechanical breaker, representing an electrical circuit of the same general class as that of the low tension system. Connected across the points of the breaker however is a condenser. Wound in mutual inductive relation to the primary coil is a secondary winding, consisting of many turns of fine wire, for transforming the energy to a higher potential than is possible with the primary winding under the limitations of magneto construction.

Electro-motive-forces of from 10,000 to 15,000 volts are the common practise in high tension ignition systems, and since the winding space in magnetos will permit only from 8,000 to 12,000 turns of fine gauge wires, it is evident that the e.m.f. per turn, induced during the period of break must be at least one volt.

Turning to the data taken from the oscillogram of Fig. 16, it is seen that the maximum e.m.f. induced during arc-ing is 127 volts or .212 volts per turn, and it is further

evident that this maximum occurred at a time after practically all the energy had been dissipated in an arc. The possibility of transforming energy by this method of induction, besides its mechanical drawbacks, is therefore quite apparent.

A quicker means of handling the stored electro-magnetic energy is necessary and the condenser is called upon to perform this function, because of the fact that the production of an electro-static field is one of the quickest electrical phenomena. Without the presence of the secondary to absorb energy, the condenser would have to handle practically all the stored primary energy and as the induced e.m.f. in high tension magnetos will reach only from 1.0 to 1.5 volts per turn as the maximum, it is evident that the condenser capacity would have to be excessive. But the secondary absorbs most of the energy during sparking so that high tension magnetos require condensers of only .15 to .25 micro-farads.

The electrical system represented in the high tension magneto can be expressed simply, as a short circuited generative and inductive winding, that at break across a condenser, tends to become an electrically oscillatory circuit, but is dampened by an arcing secondary winding. The arc from the secondary is of course utilized as the ignition spark.

It is evident, that the condenser in this system is the most important electrical consideration, for the successful electrical operation depends upon its functions. Besides the quick magnetic change it produces in the magneto, it also serves to protect the breaker points.

Inspite of the fact that the primary of the high

tension magneto must occupy much less space than it did in the low tension system, and is therefore of fewer turns and usually of heavier gauge wire, its general action on short circuit will be the same in a qualitative way as that of the low tension magneto. Quantitatively, its generative strength will be practically the same, though the components of this energy will be quite different. The only material difference between the action of the low tension magneto and the high tension one is therefore in the phenomena of transformation that occurs during sparking.

As to the relative efficiencies of the two different types of systems, considered from an electrical standpoint, there is no doubt but what the low tension system delivers more of the generated and stored energy to the spark than does the high tension system. The chief difference between the two system efficiencies is in the iron losses, which for the high tension system must be higher because of the quicker magnetic action. The quicker action of the high tension system has a tendency to reduce the copper loss in the primary over that occurring in the low tension system, but has to compensate for it, the added copper loss of the secondary circuit. The period of sparking for the high tension system is very much shorter than that of the low tension system, so that even if the energy delivered is not quite as much, nevertheless, it must have a higher maximum power value than is received in the low tension system. The quickness and high power value of the high tension ignition spark make it very effective for the high speed engine in which the period of combustion is necessarily very short.

It is not the intention of the writer to go into any

detail of analysis of the high tension magneto in this paper, but to include the above paragraphs only as a supplement to the analysis of the low tension system. The basis of an efficient high tension magneto is an efficient low tension generator so that an analysis of a high tension magneto would have to be begun along the same lines as that represented in the previous chapters. The study of the sparking phenomena of the high tension system is very much more difficult than that of the low tension spark because of the shortness of its period. However an approach can be made in the same way as is shown in the discussion of sparking phenomena, with the exception that it is impossible to measure the secondary e.m.f.-time variations.

There are no standardized methods of magneto design, based upon mathematical calculations such as have been perfected in other electrical engineering pursuits, because of the small amount of energy involved and because of the fact that the phenomena are purely transients. Cut and try as the methods usually are, and dependent upon the judgment of the engineer as they only can be, yet the writer trusts that in this treatise he has illustrated the value of a qualitative understanding of the phenomena involved and the use of the oscillograph in studying ignition system performances. It is very evident that the oscillograph reduces even cut and try methods to a scientific certainty.